RELATIONSHIP BETWEEN SUBJECTIVE RESPONSES AND PHYSICAL PARAMETERS FOR AIR-CONDITIONER NOISE

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Both the sound level and the sound quality of an air conditioner are important for the user's acoustic comfort. The aim of this paper is to determine the factor that is most influential on the subjective responses caused by this noise. Sound quality can be characterized by psychoacoustic factors including loudness, sharpness, roughness, and fluctuation strength or factors obtained from autocorrelation function (ACF) of a sound. Subjective annoyance and preference was evaluated using a paired comparison method. Multiple regression analyses were performed using a linear combination of the psychoacoustic or the ACF factors, and their standard deviations. The results indicated that subjective responses can be predicted by the psychoacoustic or the ACF factors.
Keywords: air-conditioner noise, sound quality, subjective assessment

1. Introduction

Large electrical appliances such as air conditioners, refrigerators, and washing machines are regarded as major noise sources in building environments. Air conditioners are widely used in classrooms, offices, and residences for long periods, and thus considerable efforts have been made to reduce the sound levels of these devices during operation. As results, the sound levels of air conditioners are now comparatively low [1, 2]. However, people may still be made to feel uncomfortable by certain aspects of the sound quality, even when the actual sound level of the air conditioners is low [3]. Therefore, both the sound levels and the sound quality of an air conditioner are important for the user's acoustic comfort.

Several studies have evaluated the relationships between sound quality metrics (termed psychoacoustic factors) such as loudness, sharpness, and roughness [4] and subjective factors such as similarity, annoyance, and pleasantness for air-conditioner noises [5, 6]. The results indicated that psychoacoustic factors can influence subjective responses. As with other psychoacoustic factors, autocorrelation function (ACF) factors are significantly correlated with subjective responses [7]. In this study, I address the ACF factors implicated in the evaluation of air-conditioner noise quality to clarify the parameters that most strongly influence subjective responses to air-conditioner noises. One rationale for the ACF approach is that the perception of the quality of most sounds is based on information that is embedded in the timing of the spikes in the sound, i.e., the temporal correlation representations arise from spike timing patterns in the auditory nerve, and this is reflected in the ACF of the sound [8, 9]. Another rationale is that the ACF factors describe the basic temporal sensations, such as pitch, loudness, or timbre [10, 11]. In addition, ACF analysis is simple compared with psychoacoustic factors, which require complex calculations [4].

The aim of this study is to determine the factor that is the most dominant in terms of the subjective assessment caused by air-conditioner noise. Air-conditioner noises measured in buildings and cars were used in this study.

2. Methods

2.1 Measurements of air-conditioner noises

Air-conditioner noise generated by two cassette-type (CT1 and CT2) and five split-type air conditioners (ST1, ST2, ST3, ST4 and ST5), and one central air-conditioner system (CA), were measured at two or three operational levels (high, middle, or low) using an omnidirectional microphone. The microphone was placed just below the cassette-type air conditioners, in front of the split-type air conditioners, and at the position where the noise from the central air conditioning system was most clearly heard. Although no wind screen was used, the microphone was set such that it was not placed directly in the path of the air currents. For all measurements, the noise was recorded via an analog-to-digital/digital-to-analog (AD/DA) converter at a sampling rate of 44.1 kHz and with a sampling resolution of 24 bits.

Air-conditioner noises in two different cars (A and B) were measured. The car windows and doors were always closed and the air-conditioner system was operated with the car engine off during the recording. While not simulating actual driving conditions, these test conditions eliminated possible effects of noise from the engine and road conditions on subjective preference for air-conditioner sounds. The effects of these other noises will be examined in future experiments. The air-conditioner systems in the cars under investigation had three air outlets, here called Face, Foot, and Def. Face and Foot modes allow the air to flow to the driver's face and feet, respectively. Def mode enables the air to flow to the windshield to defrost the glass. An omnidirectional microphone was placed at ear height with respect to the driver's sitting position. A driver always occupied the driver seat, but fellow passengers were not always in other seats. The focus was on the effects of the sound source, not the position of the listener; thus, the microphone was only set toward the driver's position. For all measurements, the sound was recorded via an AD/DA converter at a sampling rate of 48 kHz and with a sampling resolution of 16 bits.

2.2 Analysis of air-conditioner noises

Sound quality evaluation has focused on psychoacoustic factors including loudness, sharpness, roughness, and fluctuation strength [4]. Loudness is the psychological counterpart to the physical strength of a sound. In this study, I considered non-stationary time-varying loudness [12]. Sharpness is a measure of the high frequency content of a sound, where a higher proportion of high frequency components indicates a sharper sound. The sharpness of a sound can be calculated via the addition of a weighting function to its specific loudness spectrum [4]. Roughness quantifies the subjective perception of the rapid (15–300 Hz) amplitude modulation of a sound. Roughness is generally calculated using the time-varying loudness multi-spectrum. For this study, I used a modified version of the roughness calculation [13]. I evaluated fluctuation strength, which is similar in principle to roughness, but reflects the subjective perception of the slower (at frequencies up to 20 Hz) amplitude modulation of a sound. The sensation corresponding to fluctuation strength persists for the sound components up to 20 Hz, where roughness dominates for the higher frequencies. Fluctuation strength is also calculated using the time-varying non-stationary loudness multi-spectrum [4]. I calculated the loudness, sharpness, roughness, and fluctuation strength. The size of the temporal window used for analysis was 0.5 s. Analyses were conducted using a MATLAB-based analysis program.

The ACF factors for sound quality evaluation have been previously proposed [10, 11]. To calculate the ACF factors, the normalized ACF of the signal recorded from microphones, $p(t)$, as a function of the running step, s, is defined by

$$\phi(\tau) = \phi(\tau; s, T) = \frac{\Phi(\tau; s, T)}{\sqrt{\Phi(0; s, T)\Phi(0; s+\tau, T)}}, \qquad (1)$$

where

$$\Phi(\tau; s, T) = \frac{1}{2T}\int_{s-T}^{s+T} p'(t)\,p'(t+\tau)\,dt. \qquad (2)$$

Here, $2T$ is the integration interval and $p'(t) = p(t)*s_e(t)$, where $s_e(t)$ is the ear sensitivity. In this study, $p(t)$ is the signal that was measured using an omnidirectional microphone. $s_e(t)$ represents the impulse response of an A-weighted network, including the transfer functions of the human outer and middle ear, for convenience [10, 11]. Normalization of the ACF is performed using the geometric mean of the energy at s and the energy at $s+\tau$; this ensures that the normalized ACF satisfies the condition $0 \leqslant \phi(\tau) \leqslant 1$.

L_{Aeq} is determined based on the A-weighted $p(t)$ signal as a function of s. L_{Aeq} is then calculated using

$$L_{Aeq}(s,T) = 10 \log \Phi(0; s, T) . \qquad (3)$$

This means that the ACF includes L_{Aeq} as a factor.

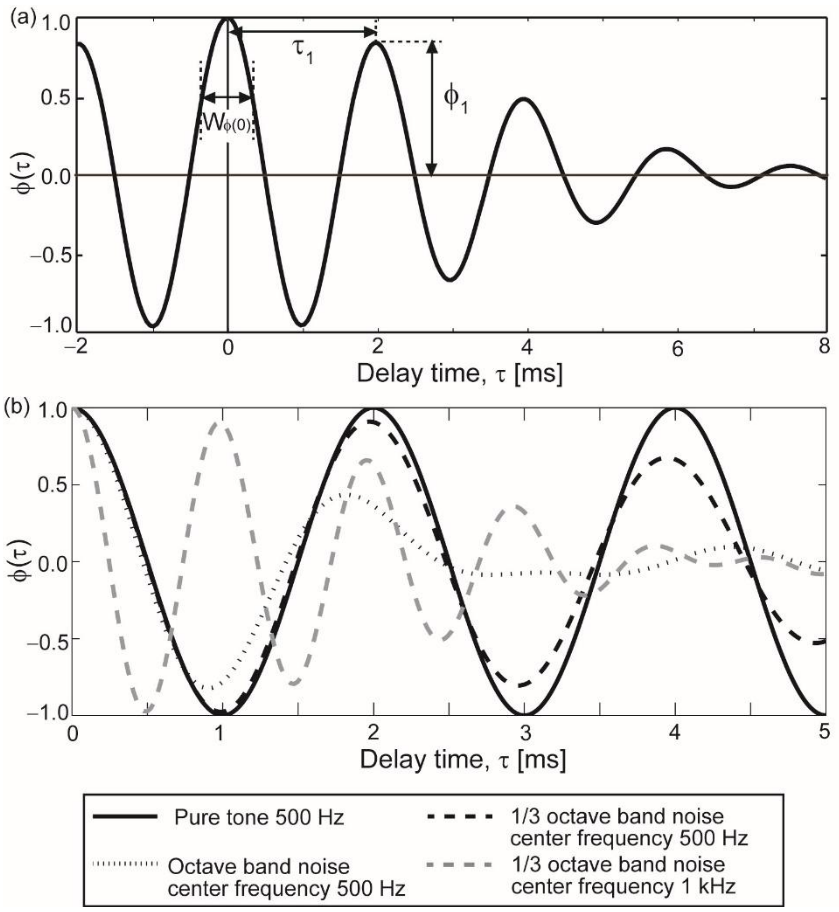

Figure 1: (a) Definitions of the ACF factors, τ_1, ϕ_1, and $W_{\phi(0)}$. (b) Examples of ACF for a pure tone, octave, and 1/3 octave band noise.

The other ACF factors are calculated from the normalized ACF. τ_1 and ϕ_1 are defined as the time delay and the amplitude of the first maximum peak as shown in Fig. 1(a). τ_1 and ϕ_1 are related to the perceived pitch and the pitch strength of the complex sounds, respectively [10, 14]. Figure 1(b) shows the ACFs for a 500 Hz pure tone, the 1/3 and 1/1 octave band noises at a center frequency of 500 Hz, and the 1/1 octave band noise at a center frequency of 1 kHz. Sounds with a low center frequency have larger τ_1 values. In contrast, sounds with wide bandwidths have a lower ϕ_1 value. Therefore, higher values of τ_1 and ϕ_1 indicate that the sound has a lower pitch and a stronger pitch, respectively. The other ACF factor, $W_{\phi(0)}$, is defined using the delay time interval at a normalized

ACF value of 0.5, as shown in Fig. 1(a), and represents the width of the first decay. $W_{\phi(0)}$ is equivalent to the spectral centroid because the correlation coefficient between $W_{\phi(0)}$ and the spectral centroid when calculated from a pure tone, the 1/1 and 1/3 octave band noises, the white noise, and the pink noise, is 0.98 [11]. The 1/3 octave band noise at a center frequency of 1 kHz has a smaller $W_{\phi(0)}$ than that at a center frequency of 500 Hz, as shown in Fig. 1(b). Higher values of $W_{\phi(0)}$ indicate that the sound includes a higher proportion of low frequency components. I calculated the τ_1, ϕ_1, and $W_{\phi(0)}$ for air-conditioner noises as a function of time. The integration interval was $2T$ = 0.5 s and the running step was s = 0.1 s in all calculations. The analyses were conducted using a MATLAB-based analysis program.

2.3 Subjective assessments

Subjective annoyance caused by air-conditioner noise measured in buildings was evaluated to clarify the effects of the sound quality indices on annoyance. Fourteen participants took part in the experiments. To clarify the effects of the sound quality indices on subjective preference and to evaluate the effects of atmospheric temperature on subjective preference, I also evaluated subjective preference for air-conditioner noises measured in cars. Twelve and ten participants took part in the experiment in summer and winter, respectively. All participants had normal hearing, no history of neurological disease, and ranged in age between 20 and 40 years. Informed consent was obtained from each participant after the nature of the study had been explained. The study was approved by the ethics committee of the National Institute of Advanced Industrial Science and Technology (AIST) of Japan.

Eight stimuli were selected from the measured air conditioning noise in buildings. These stimuli were CT1, CT2, ST1, ST4, ST5 and CA at the low level and ST2 and ST3 at the high level. The duration of each stimulus was 2.5 s. The stimuli were presented binaurally through headphones (HD650, Sennheiser). The monaural signal measured by the omnidirectional microphone was presented binaurally at the same L_{Aeq} as the actual measured stimuli. L_{Aeq} was verified using a dummy head microphone (KU100, Neumann) and a sound calibrator (Type 4231, B&K).

The recorded air-conditioner noises from car A in the Face, Foot, and Def modes and those from car B in the Face and Foot modes were used for the preference test. The duration of each stimulus was 2.0 s. The monaural signal recorded by the omnidirectional microphone was presented binaurally through headphones (HD650, Sennheiser) in a soundproof room at L_{Aeq} of 50, 60, and 70 dBA. L_{Aeq} was verified using a dummy head microphone (KU100, Neumann) and a sound calibrator (Type 4231, B&K). The air temperature of the room was 25 ± 1 and 21 ± 1 degrees in summer and winter, respectively.

Scheffe's paired comparison tests [15] were performed for all combinations of pairs of stimuli, by interchanging the order in which the stimuli in each pair were presented in each session and by presenting the pairs in random order. The rise and fall times were 100 ms, and the silent interval between stimuli was 1.0 s. After the presentation of each pair of stimuli, the participants were required to compare the two stimuli in each case based on seven grades by considering the differences between the two stimuli.

The averaged scale values of annoyance and preference according to each participant were calculated based on the modified Scheffe's method [16]. Analysis of variance (ANOVA) was then conducted on the results of the paired comparison experiments. To calculate the effects of each objective factor on participant annoyance and preference, multiple regression analyses were conducted using a linear combination of L_{Aeq}, the ACF factors and their standard deviations (SDs) as predictive variables by stepwise procedures in model 1. The predictive variables were the loudness, sharpness, roughness, fluctuation strength, and their SDs in model 2. The analyses were carried out using SPSS statistical analysis software (SPSS version 22.0, IBM).

3. Results

3.1 Subjective annoyance for air-conditioner noise measured in buildings

ANOVA for the scale value of the annoyance revealed that the primary effect (i.e., the differences between the air-conditioner noises) was statistically significant ($p < 0.01$). There was a statistically significant interaction between the primary effect and the participant. However, there were no significant effects caused by the combination of the stimuli. The relationships between the averaged scale value of the annoyance and each factor are presented in Fig. 2. Annoyance was found to increase with increasing L_{Aeq}, loudness, roughness, and fluctuation strength, and with decreasing τ_1, suggesting that components that were louder, were subject to greater amplitude modulation, or were at a higher pitch caused greater levels of annoyance.

A multiple linear regression analysis was performed with the scale values of annoyance for all participants as the outcome variable. The final version for model 1 indicated that τ_1, ϕ_1, and the SD of ϕ_1 were the significant factors:

$$SV_{\mathrm{annoyance}} \approx a_1 {*} \tau_1 + a_2 {*} \phi_1 + a_3 {*} \mathrm{SD\_}\phi_1 + b. \qquad (4)$$

The model was statistically significant ($p < 0.01$), and the modified determination coefficient was 0.87. The standardized partial regression coefficients of the variables a_1, a_2, and a_3 in Eq. (4) were −1.17, −0.61, and 0.20, respectively. The negative coefficients for τ_1 and ϕ_1 indicate that the higher pitch components and weaker pitch strength of the noise cause greater annoyance.

The final version for model 2 indicated that the loudness, the SD of the roughness, and the roughness were the significant factors:

$$SV_{\mathrm{annoyance}} \approx c_1 {*} \mathrm{loudness} + c_2 {*} \mathrm{SD\_roughness} + c_3 {*} \mathrm{roughness} + d. \qquad (5)$$

The model was statistically significant ($p < 0.01$) and the modified determination coefficient was 0.87. The standardized partial regression coefficients of the variable c_1, c_2, and c_3 in Eq. (5) were 0.50, 0.35, and 0.12, respectively. The positive coefficients for loudness, roughness, and SD_roughness indicate that louder and higher rapid amplitude modulation and the fluctuation of the noise cause greater annoyance.

3.2 Subjective preference for air-conditioner noise measured in cars

The ANOVA for the scale values of preference revealed that the primary effect was statistically significant in summer ($p < 0.01$) and winter ($p < 0.01$). I found a statistically significant interaction between the primary effect and the participant in summer ($p < 0.01$) and winter ($p < 0.01$).

A multiple linear regression analysis was performed with the scale values of preference for all participants as the outcome variable. The final version of model 1 indicated that L_{Aeq}, ϕ_1, and $W_{\phi(0)}$ were significant factors in summer and winter:

$$SV_{preference\ in\ summer} \approx e_1 {*} L_{Aeq} + e_2 {*} \phi_1 + e_3 {*} W_{\phi(0)} + f_1, \qquad (6)$$

$$SV_{preference\ in\ winter} \approx e_4 {*} L_{Aeq} + e_5 {*} \phi_1 + e_6 {*} W_{\phi(0)} + f_2. \qquad (7)$$

The model was statistically significant for the summer experiment ($p < 0.01$) and the modified determination coefficient was 0.87. The standardized partial regression coefficients of the variables e_1, e_2, and e_3 in Eq. (6) were −0.83, −0.14, and 0.12, respectively. The model was also statistically significant for the winter experiment ($p < 0.01$) and the modified determination coefficient was 0.88. The standardized partial regression coefficients of the variables e_4, e_5, and e_6 in Eq. (7) were −0.85, −0.13, and 0.13, respectively.

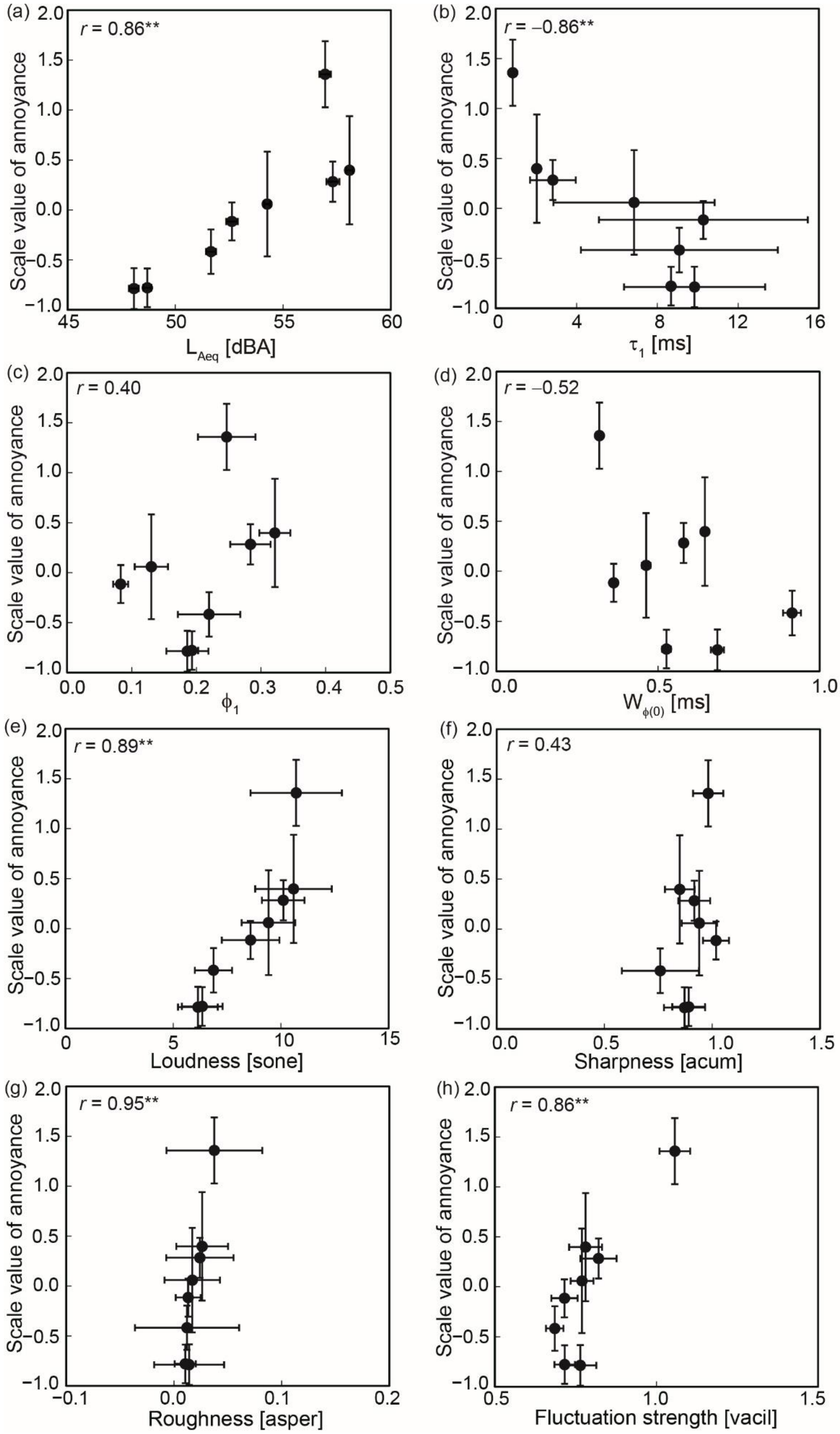

Figure 2: Relationships between the scale value of annoyance and (a) L_{Aeq}, (b) τ_1, (c) ϕ_1, (d) $W_{\phi(0)}$, (e) loudness, (f) sharpness, (g) roughness, or (h) fluctuation strength. Error bars indicate standard deviations. Asterisks represent the level of significance, i.e., ** $p < 0.01$.

The final version of model 2 indicated that loudness and sharpness were significant factors in summer, while loudness and fluctuation strength were significant factors in winter:

$$SV_{preference\ in\ summer} \approx g_1\text{*loudness} + g_2\text{*sharpness} + h_1, \quad (8)$$

$$SV_{preference\ in\ winter} \approx g_3\text{*loudness} + g_4\text{*fluctuation strength} + h_2. \quad (9)$$

The model was statistically significant for the summer experiment ($p < 0.01$), and the modified determination coefficient was 0.87. The standardized partial regression coefficients of the variables g_1 and g_2 in Eq. (8) were −0.83 and −0.17. The model was also statistically significant for the winter experiment ($p < 0.01$), and the modified determination coefficient was 0.87. The standardized partial regression coefficients of the variables g_3 and g_4 in Eq. (9) were −0.67 and −0.25.

4. Discussion and conclusions

In this study, relationships between subjective annoyance for air-conditioner noises and sound quality factors were investigated. Subjective annoyance increased with decreasing τ_1 and ϕ_1, and increasing L_{Aeq}, loudness, and roughness. A previous study on annoyance caused by refrigerator noises indicated that the ϕ_1 is a significant factor [7], and that caused by floor impact sound indicated that the SD of ϕ_1 is also a significant factor [17]. This is consistent with the present findings. However, previous studies on annoyance caused by floor impact sound [17] and road traffic noise [18] indicated that the SD of L_{Aeq} is a significant factor, which is not consistent with the present findings. This means that the temporal fluctuation of L_{Aeq} for air-conditioner noise is smaller than that for floor impact sound and road traffic noise.

Relationships between subjective preference for air-conditioner noises and sound quality factors were also investigated. Subjective preference increased with decreasing L_{Aeq}, and loudness. This was likely because the air-conditioner sounds were presented at L_{Aeqs}, of 50, 60, and 70 dBA; the differences between these values were sufficiently large to be noticeable by the participant.

As for ACF factors, $W_{\phi(0)}$ had a significant effect on subjective preference. The correlation coefficients between preference and $W_{\phi(0)}$ was positive, suggesting that the air-conditioner noises with lower spectral centroids were more strongly preferred. Previous studies have indicated that $W_{\phi(0)}$ is significantly and negatively correlated with subjective annoyance for noises in train car [19] and station [20]. This indicates that noises with lower spectral centroids are less annoying and is consistent with the present findings.

Another ACF factor, ϕ_1, also had a significant effect on subjective preference. The correlation coefficients between preference and ϕ_1 were negative, suggesting that the air-conditioner noises with lower strength of pitch were more strongly preferred. A previous study indicated a positive relationship between subjective preference for birdsongs and ϕ_1 [11]. This is not consistent with the present findings. This difference may be due to the tonal components of birdsongs, while air-conditioner noises have no such components. Additionally, for refrigerator noise, ϕ_1 has a positive effect on subjective noisiness, meaning that noises with a lower strength of pitch are perceived as less noisy [7].

The relationships between subjective annoyance and preference for air-conditioner noises and sound quality indices, such as ACF factors, were analyzed. The results indicated that the L_{Aeqs}, τ_1, ϕ_1, and $W_{\phi(0)}$ were significantly influential factors in the subjective annoyance or preference for air-conditioner noises. Lower L_{Aeq} and ϕ_1 were associated with higher preference, meaning that air-conditioner sounds with quieter levels and weaker pitch strength are more strongly preferred. Higher $W_{\phi(0)}$ led to higher preference, meaning that air-conditioner sounds with lower spectral centroids are more strongly preferred. As we controlled for temperature, these results are not influenced by the temperature of the atmosphere.

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